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Study of the moisture behavior of newly developed plasters applied on brick pillars

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Abstract

As part of research works devoted to the development of silicate thermal insulation materials, two mixtures of plasters based on lightweight aggregate and on traditional and alternative binders were designed. The laboratory-prepared plasters were applied to masonry columns, in which probes were incorporated for monitoring changes in moisture. After the plasters had hardened, the structure fragments were flooded with water of a constant level for the whole duration of the long-term measurement. For monitoring the moisture profile, 2 methods of measurement were used. It was electrical impedance spectrometry and determination of moisture content using a capacitive hygrometer.

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Keywords: Thermal insulation plasters; thermal conductivity; capillary absorption coefficient; moisture transport; porosity

1. Introduction

Moisture is one of the factors which have a strong influence on the thermal insulating function of building materials. The development of thermal insulation plasters therefore requires materials that possess good thermal-technical properties and can be applied in places with high moisture. For decades now, The Faculty of Civil Engineering of Brno University of Technology has been concerned with research in new promising and eco-friendly plasters with excellent thermal insulation properties. This research often uses not only conventional raw materials but also alternative ones, mainly those which put a low impact on the environment. Another important property is

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the porosity of the materials. It is closely connected with the capillary activity of plasters, which comes into play especially in implementing those parts of a building exposed to moisture [1,2,3].

Many domestic as well as foreign experts deal with the development of thermal insulation plasters. There is a visible trend in terms of incorporating natural raw materials as well as making use of a number of chemical additives for improving the plaster properties, mainly air-entraining agents and hydrophobizers [2,3,4,5,6,7,8].

The paper focuses mainly on the investigation of the moisture progression of 2 mixtures of newly developed thermal insulation plasters applied on fragments of a structure that was permanently subjected to moisture load. For comparison, 1 fragment had a reference plaster applied. It was a thermal insulation plaster widely available on the construction market in the EU. The goal was mainly the investigation of the capillary activity of the new plasters and their possible application.

Nomenclature

Z	electrical impedance
R	electrical resistance
U	voltage
I	current
j	complex number unit
X	reactance
G	electrical conductance
f	frequency
r	radius of pore
g	acceleration
γ	surface tension
Θ	contact angle

2. Materials and methods

The raw materials were selected based on previous studies and research in the development of thermal insulation plasters. Lightweight aggregate based on expanded glass supplemented by milled limestone constituted the basis of the matrix of the new mixtures (Mixture 1 and 2). The binders used were cement CEM I 42.5 R (Mixture 1) and white cement CEM I 52.5 R (Mixture 2) combined with metakaolin; a pozzolana active admixture. These mixtures were used mainly for the purpose of observing the influence of chemical additives. Mixture 1 contained additives based on hydroxyethyl cellulose and methyl cellulose, in order to improve its workability in fresh state, and an air-entrainment additive based on olefin sulfonates. Mixture 2 contained the same chemical additives, but in a different ratio, and in addition to those, also a hydrophobing agent based on oleates and stearates. The detail of the composition of the mixtures is in Table 1 below.

Table 1. Composition of mixtures (*g*)

Component	Mixture 1	Mixture 2
Lightweight aggregate	9182	9182
Finely ground limestone	1888	1888
Lime hydrate	1328	1328
CEM I 42.5R	664	-
CEM I 52.5R white	-	1000
Metakaolin	664	664
Chemical additives	130	330
Water	10000	8086

A total of 3 mixtures of thermal insulation plasters were prepared for the testing (1 reference, 2 newly designed). These were then applied on masonry pillars with moisture sensors built in. The pillars served as a reference surface for the application of the plasters. After the plasters had cured, the pillars were exposed to constant moisture. Figure 1 shows a diagram of a pillar with the positioning of 2 horizontal and 1 vertical moisture sensor rods. The short sensor rods were 290 mm long, with 6 electrodes and were fitted horizontally, at the height of 325 mm and 585 mm; the long sensor rod, 475 mm long, with 10 electrodes was fitted vertically down the middle of the masonry pillar, 305 mm above the bottom edge. The goal was to map the moisture profile of the plasters, simulate the behaviour of these materials at increased moisture of the masonry and observe their capillary activity.

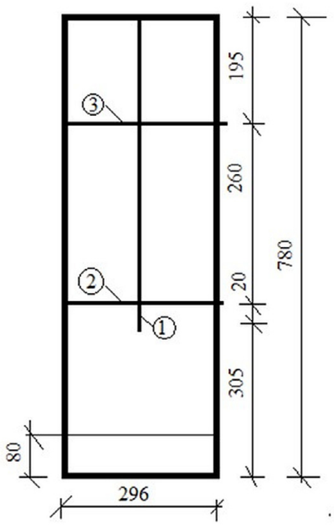

Fig. 1. Design of pillar with horizontal (2, 3) and verticals (1) probes.

Samples were taken from all three mixtures of fresh mortars prior to being applied to the masonry segments so that specimens could be made to be used in further laboratory tests of basic physical and thermal insulation properties.

The following tests were performed with the fresh mortars: Determination of bulk density of fresh mortar (according to EN 1015-6) and Determination of consistence of fresh mortar (according to EN 1015-3).

The hardened mortars were tested for the following properties: bulk density of hardened mortar (according to EN 1015-10), thermal conductivity by non-stationary hot wire method (according to EN ISO 8894-1), capillary absorption coefficient of hardened mortar (according to EN 1015-18) and porosity. Porosity was determined by means of mercury intrusion porosimetry that operates on the basis of capillary depression. When a porous solid material is submerged in mercury, which does not wet it (i.e. the contact angle is greater than 90°), the mercury can only enter the pores by the action of external pressure. This pressure must be the greater, the smaller the pores to be filled. This dependency is quantitatively expressed in 1921 in Washburn's equation:

$$g \cdot \rho \cdot h \cdot \pi \cdot r \cdot 2 = -2 \cdot \pi \cdot r \cdot \gamma \cdot \cos \Theta \qquad (1)$$

where g ($m \cdot s^{-2}$) is acceleration, ρ ($g \cdot m^{-3}$) is mercury density, h (*m*) is the height of the column of mercury in the pore, r (*m*) is the radius of a circular pore, γ ($N.m^{-1}$) is the surface tension of mercury in a pore and Θ is the contact angle of the pore walls for mercury. The equation can be written as:

$$g \cdot \rho \cdot h \cdot = -2 \cdot \gamma \cdot \cos \Theta / r \tag{2}$$

where P ($N \cdot m^{-2}$) is the total pressure under which mercury intrudes the pore.

The radius of a filled pore is thus inversely proportional to the value of pressure applied. This means that the pores of the highest radius are filled at the lowest pressure and each pressure increment causes the mercury to intrude into a fraction of pores of a corresponding smaller radius.

Non-destructive methods were used for determining the moisture profile and water content of the plasters. The moisture profile of the masonry and the plasters was mapped by means of electrical impedance spectrometry. EIS is a progressive method for the determination of humidity distribution, used for wide range of applications. The basic principle of EIS is the measurement of the frequency characteristic of electrical impedance Z of porous building materials. Electrical impedance is the basic property characterizing electrical alternating-current circuits. It is always higher than or equal to the real electrical resistance R in the circuit. Apparent resistances, i.e. inductance – the reactance X_L of an inductor and capacitance – the reactance X_C of a capacitor, form the variable and thus also frequency-dependent part of electrical impedance. Electrical impedance, therefore, is composed of the real and imaginary parts. The real part is formed by the resistance R, which is frequency-independent. The imaginary part is formed by the reactance X, which is frequency-dependent. Electrical impedance can be expressed using Ohm's law for alternating-current circuits, i.e. the relation between the phasor of electrical voltage U and the phasor of electrical current I [9].

$$Z = \frac{U}{I} \tag{3}$$

The values of electrical impedance are expressed in ohms (Ω), as in the case of the values of resistance R in direct-current circuits.

The frequency characteristic of electrical impedance Z can be expressed as a function of a complex variable in the algebraic (component) form.

$$Z = R + j \cdot X \tag{4}$$

The absolute value, the modulus of electrical impedance vector $|Z|$, is expressed by the relation

$$|Z| = \sqrt{R^2 + X^2} \tag{5}$$

And the phase shift

$$\varphi = arctg\left(\frac{X}{R}\right) \tag{6}$$

Resistance R, or its inverted value of electrical conductance G – 1/R, changes with water content in the measured profile assuming a constant temperature and constant ion composition of the environment being measured. Reactance X expresses the characteristics of the measured environment, i.e. it changes with density, particle size of the sand component, pore and solid particle distribution, etc.

The Z-meter device was used for our measurement. It was developed by assoc. professor Jana Parilkova and her team in a laboratory of hydraulic research at Brno University of Technology [10].

A capacitive hygrometer GMK 100 was used for measuring moisture content. Moisture was continuously observed in the same places; both in the bottom part of the fragment as well as in the top part. A total of 10 measurements were performed whose readings were afterwards averaged.

3. Results and discussion

While specimens were being prepared in a laboratory, tests were performed on all 3 fresh test mixtures. The evaluation of selected properties is in Table 2 below.

Table 2. Selected properties of mortars in fresh state.

Component	Flow value (*mm*)	Bulk density ($kg{\cdot}m^{-3}$)
Reference Mixture	200	786
Mixture 1	160	512
Mixture 2	135	534

The obtained data show that both mixtures exhibit lower bulk density and lower flow value (i.e. their consistency is stiffer) compared with the reference thermal insulation plaster available on the construction market.

Next, specimens for testing of selected basic physical and thermal insulation properties were made. A total of 15 bar specimens were made, with the dimensions of 40 × 40 × 160 mm. The specimens were then conditioned in laboratory conditions at 23±2 °C and relative humidity of 50% while they cured. After 28 days, the specimens were subjected to laboratory testing. The evaluation of the selected properties of the hardened mortars is in Table 3 below. Figure 2 shows a graph of the volume representation of individual pores determined by means of mercury intrusion porosimetry. Figure 3 shows the evaluation of thermal conductivity after 28 days and in dry state.

Table 3. Selected properties of mortars in hardened state.

Mixture	Bulk density - 28 days ($kg{\cdot}m^{-3}$)	Bulk density – dry state ($kg{\cdot}m^{-3}$)	Porosity (*%*)
Reference Mixture	478	478	70.7
Mixture 1	311	307	75.1
Mixture 2	354	348	69.8

The result evaluation in Table 3 shows that the porosity of the test mixtures ranges from 70 to 75%. Therefore, it can be stated that the air-entraining agents were effective in terms of pore matrix formation. The bulk density in hardened state of the newly designed mixtures is lower compared with the plaster available on the construction market. In the new mixtures, these values ranged from 307 $kg{\cdot}m^{-3}$ to 348 $kg{\cdot}m^{-3}$. This is closely connected with the plasters' thermal insulation properties, which are significantly better than those of the reference plaster. The lowest values in the dry state were found in Mixture 1, 0.0702 $W{\cdot}m^{-1}{\cdot}K^{-1}$. It can also be observed that there was no significant difference in the values of thermal conductivity after 28 days and in the dry state. Thus the assumption can be made that the newly designed plasters have a lower sensitivity to temperature which is beneficial in terms of deterioration of thermal insulation properties due to moisture.

Another observed property was the capillary absorption coefficient. It was evaluated both in case of the plasters' application as traditional plasters and as rehabilitation plasters. Table 4 below shows the overall evaluation of results for both types of plaster.

Table 4. Evaluation of the capillary absorption coefficient.

Component	Capillary absorption coefficient (rehabilitation plasters) ($kg{\cdot}m^{-2}$)	Capillary absorption coefficient (traditional plasters) ($kg{\cdot}m^{-2}{\cdot}min^{-0,5}$)	Height of capillarity (*mm*)
Reference Mixture	8.05	0.25	20
Mixture 1	4.05	0.05	15
Mixture 2	0.95	0.00	2

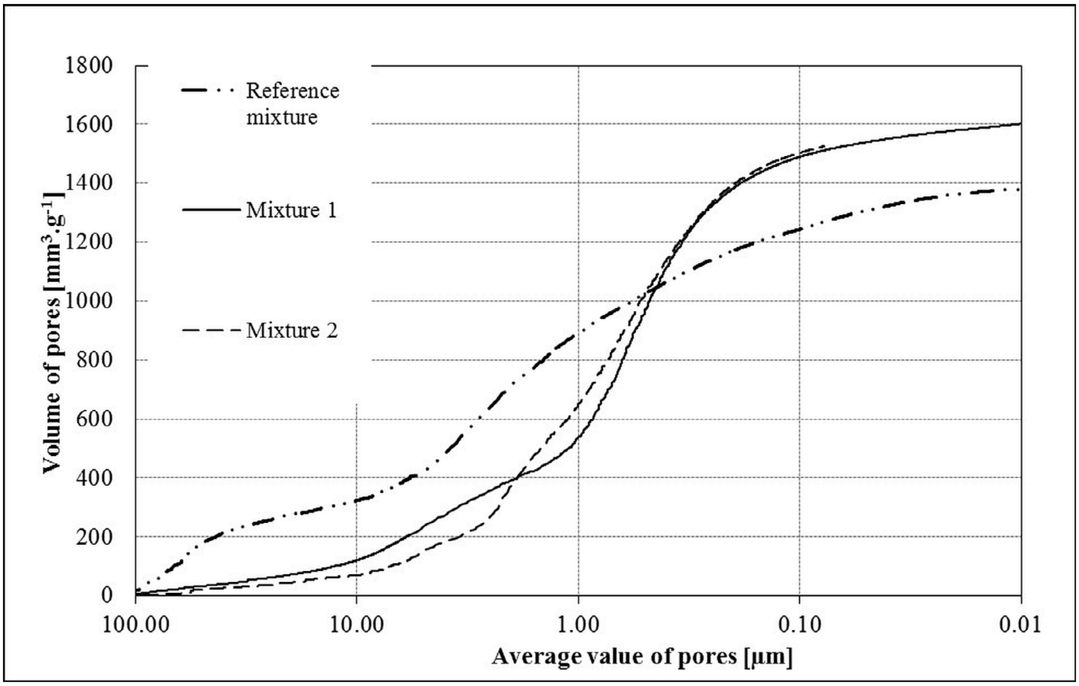

Fig. 2. Graphic representation of individual volume of pores.

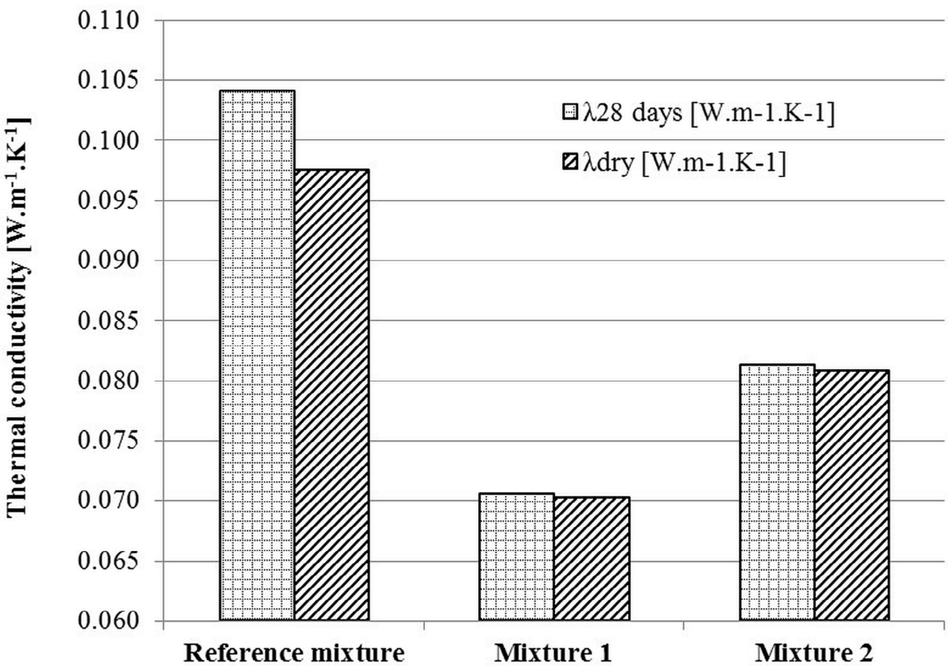

Fig. 3. Overview of values of thermal conductivity after 28 days and in dry state.

According to EN 998-1 the mixtures can be classified into following categories: Reference Mixture as W1 ($c \leq 0.4$ kg·m^{-2}·min$^{-0.5}$); Mixtures 1 and 2 as W2 ($c \leq 0.2$ kg·m^{-2}·min$^{-0.5}$).

The fresh plasters were applied on the masonry pillars, which were placed in circular plastic containers with the diameter of 600 mm. During the long-term testing, a constant water level of 80 mm was maintained in the containers. This way it was possible to monitor rising damp over a long period of time together with its influence on the moisture behaviour of the plasters, which was observed non-destructively, using a capacitive hygrometer.

Based on the results of these measurements, it can be said that after the plasters had been applied, all the pillars saw a gradual increase of moisture over the 28 days. Afterwards, the 2 newly designed plasters exhibited a gradual decrease in moisture, which was caused by the open capillary system and gradual moisture stabilisation. This shows the effective influence of the hydrophobing agents. This phenomenon of gradual drying can be observed in the recording of the moisture profile of the embedded sensors. Figure 4 shows an example of the evaluation of the values of electrical conductance G obtained with the long, vertical sensors placed in 305 mm from the bottom of the pillar.

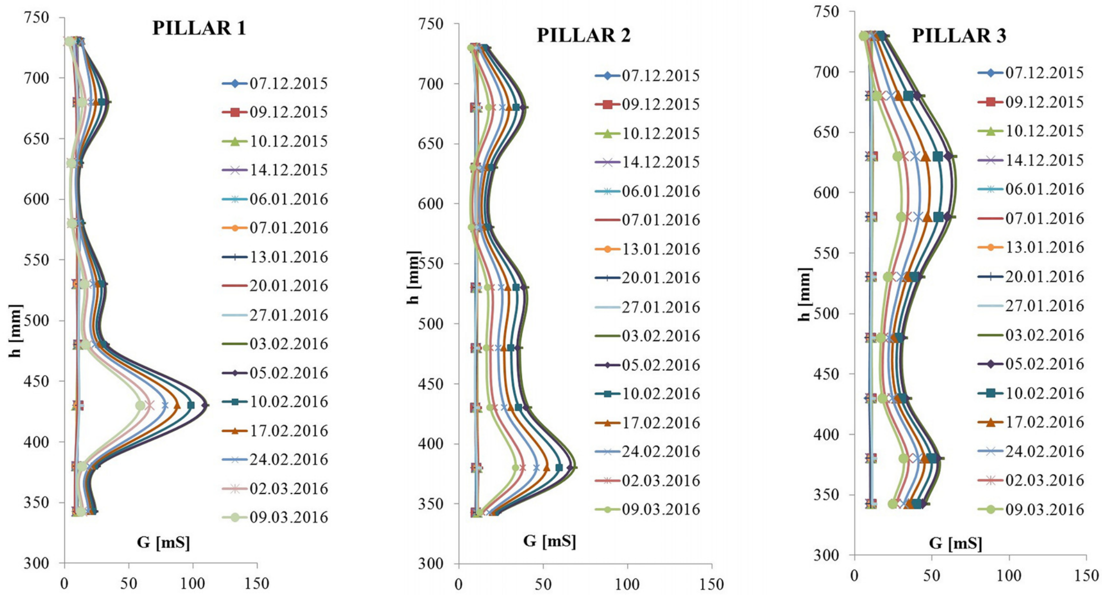

Fig. 4. Electrical conductance measured with long sensor rods placed in the vertical axis.

Table 5. Water content in hardened plasters (%).

Measured after flooding (*day*)	1	7	14	21	28	35	56	70
Reference Mixture	4.34	6.8	5.82	5.23	5.97	5.97	4.33	4.18
Mixture 1	1.52	1.55	1.56	1.57	1.60	1.61	1.56	1.24
Mixture 2	2.31	2.33	2.33	2.35	2.40	2.42	2.33	2.32

4. Conclusion

The possibility of examining the behaviour of the newly developed thermal insulation materials on masonry fragments represents an effective method of laboratory mapping of the moisture behaviour of the masonry pillars, including the masonry/plaster place of contact. The use of 2 non-destructive methods for observing the moisture behaviour can provide a good overview of the possible influence of moisture on the thermal insulation plasters. It can be said that the newly developed plasters, based on the findings obtained so far, exhibit very good thermal insulation properties. Thermal conductivity ranged between 0.07 – 0.08 $W \cdot m^{-1} \cdot K^{-1}$. The effect of the hydrophobing agents is significant in comparison with the reference mixture. Both the mixtures had much lower coefficients of capillary absorption than the reference mixture. Capillary elevation of water in Mixtures 1 and 2 was also lower than that of the reference mixture (20 mm). Both Mixture 1 and 2 can be classified as W2 according to EN 998-1. The measured moisture content in the newly developed plasters is very favourable in terms of deterioration of thermal insulation properties, as it is known that increased moisture negatively influences thermal conductivity.

Acknowledgements

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